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THE RATE OF FORMATION OF RADIOACTIVE ISOTOPES IN CHONDRITES UNDER THE ACTION OF COSMIC RAYS

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For investigating the rate of formation of radioisotopes in chondrites, under the influence of cosmic rays, aluminum nuclei bombarded by protons of 120 - 660 Mev were used, since the mass number and atomic weight of aluminum correspond to their weighted average for chondrites. Semiempirical formulas are given for the cross section for formation of cosmogenic isotopes, which agree with experimental values at a proton energy of 660 Mev. Maximum formation rates are calculated for the center of chondrites of 10 cm radius, relative to their average chemical composition. The rate of formation of cosmogenic isotopes depends on the size and chemical composition of the meteorite and on their spatial distribution in the meteorites. Comparative experimental and calculated values are tabulated for various targets, proton energies, and elements.

Author

Meteorites are our only source of information about matter in space, and therefore investigators are now showing immense interest in the detailed study of their chemical and isotopic composition. Naturally, only if we have data on the composition of matter in the Earth, the Sun, meteorites, and other bodies

* Numbers in the margin indicate pagination in the original foreign text.

of the solar system will we be able to understand the processes of their formation and evolution.

Mass spectrometry of meteroites has shown considerable anomalies in the isotopic composition of a number of elements - helium, neon, argon, potassium, vanadium, and others - as compared with their terrestrial abundances. Radioactive isotopes with half-lives considerably shorter than the age of the Earth and the meteorites (about 4700 million years) have also been found in meteorites, for example Be^{10} ($T = 2.5 \times 10^6$ yrs), Cl^{36} ($T = 3 \times 10^5$ yrs), C^{14} ($T = 3 \times 10^3$ yrs) and many radioisotopes of relatively light elements with $Z \leq 28$. The sooner after their fall a radiochemical analysis of meteorites is made, the more shorter-lived isotopes will be found. Thus, in the Harleton stone meteorite, delivered to the laboratory within 10 days of its fall, it was possible to find even as short-lived an isotope as P^{32} ($T = 14$ days) (Bibl.1).

Many investigators have studied the nuclear reactions that take place in iron meteorites under the action of cosmic-ray protons by irradiating iron targets of varying thickness with artificially accelerated protons in the energy range of 100 Mev $\leq E_p \leq$ 28 Bev (Bibl.2 - 10). They were able to estimate the rate of formation of cosmogenic isotopes and the isotopic ratios for a number of elements (Ar, K, Ne, V, and others) (Bibl.5, 10, 11, 12). The results obtained from model experiments were found to be in agreement with the effects observed in iron meteorites.

This fact provides justification for an experimental simulation of the nuclear reactions taking place in stone meteorites. Meteorites of this type, accounting for about 80% of all the meteorites that fall on the Earth, have a complex chemical composition. For example, the average composition of chondrites, the predominant type of stone meteorites, can be characterized as follows (see

Bibl.13): 36.2% oxygen; 13.9% magnesium; 0.665% sodium; 1.3% aluminum; 17.2% silicon; 2.3% sulfur; 0.1% potassium; 1.36% calcium; 0.07% titanium; 0.23% chromium; 0.18% manganese; 25.7% iron; 1.4% nickel. In stone meteorites of other types (carbonaceous chondrites, calcium-poor achondrites, calcium-rich achondrites) and iron-stone meteorites (pallasites, mesosiderites) the content of some elements varies considerably (Bibl.13). For example some enstatite achondrites hardly contain any iron at all. /1220

It is exceedingly difficult to interpret the effects of the interaction of cosmic radiation, having a broad energy spectrum (the maximum number of particles have energies from several hundred Mev to 50 Bev), with the nuclei of the above elements. A further complication is the presence of a large variety of minerals and phases in meteorites (metallic, silicate, and troilite). As a result of the differences in the chemical composition of the phases, their contents of various cosmogenic isotopes will also be different.

These difficulties have been responsible for the complete lack of knowledge, today, as to the rate of formation of cosmogenic isotopes in stone meteorites. Yet only such data will make it possible to determine the causes of the marked differences observed in the cosmic ages of iron and stone meteorites. This question, too, is exceptionally important for the problem of the origin of meteorites.

The present authors have attempted to evaluate the role of the nuclear reactions between high-energy particles of primary and secondary cosmic radiation (over 100 Mev) and silicon, magnesium, calcium, aluminum, and iron nuclei in the formation of the various radioactive cosmogenic isotopes in chondrites, whose chemical composition is more or less uniform. With this object in mind, we studied the radioactive products of the interaction of protons of 120 and

660 Mev energy with nuclei of aluminum, an element whose mass number and atomic number both correspond to their respective weighted average values for chondrites.

NUCLEAR REACTION PRODUCTS IN AN ALUMINUM TARGET

The cross section for formation of the products of fission of aluminum nuclei by high-energy protons have been determined by a number of authors (see Bibl.14-21). The energy region below 300 Mev, however, has remained uninvestigated for many isotopes. We therefore devoted particular attention to the interaction products of relatively low-energy protons ($\leq$ 660 Mev). In the first place, we did this because the intensity of particles of energy under 500 Mev in the primary cosmic radiation on the orbits of the meteor swarms may well be considerably higher than in the region of the Earth's atmosphere. In fact, data on the abundance of cosmogenic Sc^{46} and Ne^{22} in ten iron meteorites show that the primary cosmic radiation which had irradiated these meteorites apparently had 2.5 times as many particles of energy from 200 Mev to 1 Bev as it had particles of energy > 1 Bev (Bibl.22). In the second place, it is well known that the mean energy of the secondary particles formed by primary cosmic radiation in the nuclei of a photographic emulsion (O, N, C, Br, and Ag) is about 150 Mev and is independent of the energy of the primary particles in the region from 300 Mev to 15 Bev (Bibl.23). Thus, data on the formation cross sections for the products of irradiation of aluminum by protons of 150 and 660 Mev energy will permit an evaluation of the role of the medium-energy portion of the secondary particles, and also of the primary particles of energy over 100 Mev, in the formation of cosmogenic isotopes in stone meteorites.

Two types of spectrally pure aluminum foil weighing (1) 1.5 mg and (2) about 1 gm were irradiated by an internal beam of protons from the synchrocyclotron of the Laboratory for Nuclear Problems of the OIYaI (United Nuclear Research Institute), at a radius corresponding to energies of 150 and 660 Mev. The target irradiation time was 5 min and 1 - 2 hrs, respectively. The proton flux was monitored from the activity of the Na^{24} formed in the aluminum by the reaction (p, 3pn). The proton flux, calculated on the basis of the excita- /1221 tion function for Na^{24}, which has been studied in detail by many workers (Bibl. 21), was varied in our experiments over the range between 3×10^{11} and 2×10^{12} protons/cm^2-sec. After irradiation the activity of the short-lived isotopes C^{11}, N^{13}, O^{15}, F^{18}, and Na^{24} was determined in the targets (1). In the targets (2) the beryllium and sodium fractions were chemically separated with carriers, and the activity of Be^7 and Na^{22}, as well as Na^{24}, was determined in them respectively.

The activity of the preparations of the individual fractions and of the irradiated Al foil was measured on an end-window counter with a mean statistical error not over 3%. The isotopes were identified by their half-lives, the type of radiation, and the energy of β- and γ-radiation. A simplified β-spectrometer and a scintillation γ-spectrometer with a 100-channel pulse analyzer were used for this purpose.

Table 1 gives the measured formation cross sections for the identified radioisotopes (the accuracy of measurement of σ_{A_i} was ± 20%). To bring out the relation $\sigma_{A_i} = f(E_p)$ (E_p is the energy of the bombarding protons) we give the corresponding value for E_p from 390 Mev to 28 Bev according to the data of other workers. It is clear that, for isotopes with $\Delta A = A_0 - A_{prod}$ (where A_0 is the mass number of the target element and A_{prod} the mass number of the product) of a value higher than ten in the energy region from 120 to 1000 Mev, σ_{A_i} will in-

TABLE 1

FORMATION CROSS SECTIONS OF RADIOACTIVE FISSION PRODUCTS OF ALUMINUM (IN KILOBARNS)

Isotope	Ep. =120 (this paper)	390—420 Mev [16]	660 Mev (this paper)		1000—1400 Mev [16]	2200 Mev [16]	5 700 Mev		10 000 Mev [21]	28 000 Mev [15]
			Experimental	Calculated			experim. [21]	calcul. [24]		
Be^7 (57.9 days)	1.03	—	4.2	(1.03)	7.6	12.7	8.3	8.5	—	7.89
C^{11} (20.4 min)	0.73	2.8	2.8	1.3 (1.2)	5.4	6.1	6.0	4.9	4.7	4.73
N^{13} (10 min)	0.62	0.78	1.4	1.7 (1.3)	1.6	~1.8	1.7	0.97	1.53	1.18
O^{15} (124 sec)	2.3	—	6.9	10.2 (1.36)	7.6	6.5	4.5	5.7	—	3.5
F^{18} (112 min)	5.9	7.3	7.5	10.2 (9.9)	7.6	7.1	7.68	5.3	6.2	6.03
Na^{22} (2.6 years)	22.1; 19 [19]	21.2	16.5	19.5 (13.2)	16.06	12.06	17.1	(43.8)	—	9.85
Na^{24} (15 hrs)	10.8 [19]	11.2 [10]	10.6 [19]	27.0 (29)	10.5 [21]	10.4 [19]	10.5 [19]	(8.8)	9.6	8.3 [21]

Note: The Numerals in brackets [ ] refer to Bibliography

crease sharply with increasing proton energy. On further increase in the proton energy, σ_{A_i} will remain practically constant. The formation cross section of the isotopes with $\Delta A < 10$ does not vary in the region of proton energy from 120 Mev to 28 Bev. The same pattern is also observed for the fission products of the iron nucleus (Bibl.5 - 10). This is of substantial importance in determining the rate of formation of cosmogenic isotopes of the principal elements of stone meteorites. Table 2 gives the values of ΔA for all cosmogenic isotopes found in meteorites, when formed from the most common elements usually found in stone meteorites. An analysis of these values shows that the most effective ΔA for most cosmogenic isotopes is considerably less than 10, except for some isotopes, for instance K^{40}, Ti^{44}, etc., which are formed only from iron (or nickel). This makes /1222 it somewhat easier to determine the rate of formation of many cosmogenic isotopes in stone meteorites than in iron meteorites, since the formation cross sections of most isotopes in iron meteorites depend significantly on the proton energy. First of all, it is therefore necessary to know the relation $\sigma_{A_1} = f(E_p)$ for all the isotopes, as well as the

TABLE 2

VALUES OF ΔA FOR COSMOGENIC ISOTOPES ON THEIR FORMATION FROM THE MOST ABUNDANT ELEMENTS OF STONE METEORITES

Isotope	*Value of ΔA*						
	O^{16}	Mg^{24}	Al^{27}	Si^{28}	S^{32}	Ca^{40}	Fe^{56}
Be^{10}	6	fr.*	fr.*	fr.*	fr.*	fr.*	fr.*
C^{14}	2	10	»	»	»	»	»
Ne^{20}	—	4	7	8	12	20	»
Ne^{21}	—	3	6	7	11	19	»
Ne^{22}	—	2	5	6	10	18	»
Na^{22}	—	2	5	6	10	18	»
Al^{26}	—	—	1	2	6	14	30
Si^{32}	—	—	—	—	**	8	24
Cl^{36}	—	—	—	—	—	4	20
Ar^{36}	—	—	—	—	—	4	20
Ar^{37}	—	—	—	—	—	3	19
Ar^{38}	—	—	—	—	—	2	18
Ar^{39}	—	—	—	—	—	1	17
K^{40}	—	—	—	—	—	**	16
Ti^{44}	—	—	—	—	—	—	12
Ca^{45}	—	—	—	—	—	—	11
Sc^{46}	—	—	—	—	—	—	10
V^{48}	—	—	—	—	—	—	8
V^{49}	—	—	—	—	—	—	7
Cr^{51}	—	—	—	—	—	—	5
Mn^{53}	—	—	—	—	—	—	3
Mn^{54}	—	—	—	—	—	—	2
Fe^{55}	—	—	—	—	—	—	1

* This isotope is formed during the nuclear reaction, as a fragment hurled off when the bombarding particle strikes the nucleus.

** Isotope formed by the reaction $(p, p\pi^+)$.

form of the energy spectrum of the primary cosmic radiation and of the secondary nucleoactive particles formed by nuclear fission. On the other hand, a calculation of the rate of formation of cosmogenic isotopes is in principle considerably more complicated for stone meteorites than for iron meteorites. The greatest difficulties are produced by the lack of experimental data on the cross section for formation of almost all principal components of stone meteorites:

calcium, silicon, magnesium, and sulfur.

ESTIMATE OF THE RATE OF FORMATION OF RADIOISOTOPES IN CHONDRITES

To estimate the rate of formation of cosmogenic isotopes of the above elements, we must first consider the fundamental laws of distribution, with A and Z, of the yields of fission products of nuclei of mean atomic weight.

Detailed study of the fission products of the Al, Cu, Co, Mn, and V nuclei showed that the values of σ_{A_i} for nuclei of various A_{prod} and Z_{prod} are described by the equation (Bibl.25):

$$\ln \sigma(A, Z) = P_{A_i} - Q - R(Z_i - S_{A_i})^2 \tag{1}$$

The parameter S characterizes the slope of the linear relation between the most probable charge and $A_{isob} - Z_0 = f(S_{isob})$; for nuclei of mean atomic weight; $\bar{S} = 0.467$. The parameter P characterizes the mean angle of slope /1223
of the relation $\ln \sigma_{isob} = f(A_{isob})$, i.e., the distribution curve of the fission products to mass. Here, P has been found to depend on the energy of the bombarding protons:

$$P = 0.11\, E^{-0.64} \tag{2}$$

where E is the energy in Bev (Bibl.26). The parameter R characterizes the steepness of the parabolas representing the dependence of the yield isobars on Z. It would seem that this quantity should not depend on A_0 nor on E_p. The parameter Q is a norming factor, fixing the scale of absolute values of σ_{A_i}. The value of Q can be found from the relation:

$$e^{-Q} = P \cdot \sigma_{A_0(\mathrm{inel.})} (R/\pi)^{1/2} \{e^{(PA_0)} - e^{(PA_0/2)}\}^{-1} \tag{3}$$

where $\sigma_{A_0(inel)}$ is the total cross section for inelastic collision. For the mean energy of cosmic radiation, $\sigma_{inel} = 0.75\, \sigma_{A_0}$ (σ_{A_0} being the geometrical cross section of the irradiated nuclei).

The numerical values of P, R, and Q (at constant S) may be found by the method of least squares from the experimental data on the formation cross sections of individual radioactive nuclei. The literature gives these values for target nuclei with A_0 between 51 and 75 (Bibl.27, 28), and the following values for the parameters of eq.(1), found from experimental irradiation of iron targets by protons of various energies. For E_p = 150 Mev, P = 0.308 ± 0.027, Q = = 12.07 ± 1.06, R = 1.61 + 0.14, S = 0.474 ± 0.001 (Bibl.6); for E_p = 660 Mev, P = 0.145 ± 0.007, Q = 3.91 ± 0.18, R = 1.65 ± 0.08, S = 0.472 ± 0.001 (Bibl.5); and for E_p = 24 Bev, P = 0.065 ± 0.08; R = 2.03 ± 0.11, S = 0.49 ± 0.01 (see Bibl.9).

For the fission products of nuclei with $A_0 < 50$, the parameters of eq.(1) have not been determined, except for an attempt (Bibl.27) to analyze experimental data of others (Bibl.16). The only values obtained were S = 0.474 and R = 2.7 ± 0.7. The latter result is considerably higher than all others previously found for this parameter (0.65 - 1.75). An attempt to find the values of these parameters from our own experimental data for the fission products of aluminum was unsuccessful, evidently on account of the inapplicability of the method of least squares to the limited number of values of σ_{A_1} that could be determined by present methods. Using the literature values of S and R (Bibl. 27), P = 0.145 obtained in our experiments on iron at E_p = 660 Mev, and Q = = -0.27 calculated by eq.(3), we obtained the values of σ_{A_1} given in parentheses in column 5, Table 1. Satisfactory agreement with experiment was noted only for F^{18}, N^{13}, and Na^{22}, while the ratio $\sigma_{exp}/\sigma_{calc}$ for the other isotopes ranged from 5 to 0.36.

Elsewhere (Bibl.24) we find the values of σ_{A_1} calculated for the fission products of aluminum at E_p = 5.7 Bev (cf.Col.9, Table 1) and P = 0.053 (taken from experiments on the irradiation of copper), with Q found from eq.(3), R = = 1.47 and S = 0.47. The maximum difference between the calculated and experimental values is 35%, and the minimum difference is -2.5% (except for Na^{22}).

Another semiempirical formula for determining the formation cross section of isobaric nuclei as a function of the proton energy and the mass number of the target element [eq.(4)] has recently been proposed (Bibl.29), on the basis of the well-known calculations by the Monte Carlo method by Metropolis et al (Bibl.30) and Dostrovsky et al (Bibl.31). Equation (5) may be used to es- /1224
timate the formation cross section of the individual nuclear species.

$$\sigma(\Delta A_i,\ A_0,\ Z_0) = \sigma_0 A_0^{2/3} \frac{C_1 \cdot E_0^{-2/3}}{1 + C_2 A_0} \cdot e^{-\left(\frac{C_1 \cdot E_0^{-2/3}}{1 + C_2 A_0}\right)\Delta A_i}. \tag{4}$$

where

$$\sigma_0 = 60 \text{ k-barns} \quad C_1 = 0.25, \quad C_2 = 0.022.$$

$$\sigma(A_i Z_i) = \sigma_{A_{isob}} \sqrt{R/\pi} \cdot e^{-R(Z_i - SA_i)^2}, \tag{5}$$

where $\pi = 3.14$, and R and S are parameters of eq.(1).

Thus, by combining these two formulas we can determine the formation cross section of all nuclei, whether stable or radioactive, for any target and various proton energies. If these formulas are sufficiently reliable, they will be extremely important for an interpretation of the effects of nuclear reactions in meteorites. For this reason, we first calculated the values of σ_{A_i} for several cosmogenic iron and aluminum isotopes by eqs.(4) and (5), and compared them with our own experimental data. Table 1, Col.5, and Table 3 show agreement of calculated and experimental values of σ_{A_i} of the radioactive isotopes at E_p = 660 Mev, and for the stable isotopes of inert gases at E_p = 540 Mev (Bibl.32). For a proton energy of 150 Mev, however, similar agreement is not noted, especially for isotopes of high ΔA; the differences amount to almost three orders of magnitude. Consequently, eqs.(4) and (5) may be used only to estimate formation cross sections of isotopes that do not depend on the energy of the bombarding particles.

TABLE 3

COMPARISON OF CALCULATED AND EXPERIMENTAL VALUES OF σ_{A_1}
FOR IRON AND ALUMINUM TARGETS AT E_p = 660 Mev

Isotope	Iron target			Isotope	Fe target			Al target		
	experim.	calc.	$\sigma_{exp}/\sigma_{cal}$		experim.	calcul.	$\sigma_{exp}/\sigma_{cal}$	experim.	calc[illegible]	[illegible] σ_{calc}
Ne^{20}	—	0.63	—	Ar^{39}	5.1*	5.78	0.88	27*	26.21	1.0[illegible]
Ne^{21}	0.8*	0.73	1.09	Sc^{46}	5.8	9.25	0.62	28*	32.4	0.86
Nc^{22}	0.6*	0.85	0.70	Ti^{44}	0.97	1.3	0.746	39.6**	39.5	1.0
Na^{22}	0.36	0.33	1.09	V^{48}	16.1	23.9	0.67	16.6	21.5	0.77
Al^{26}	0.36	0.467	0.77	V^{49}	32.4	32.3	1.0	—	44	—
Si^{32}	0.28	0.36	0.77	Cr^{51}	41.3	44.9	0.92			
Cl^{36}	3.7	4.85	0.76	Mn^{53}	74.4	60.7	1.22			
Ar^{36}	4.4	6.7	0.65	Mn^{54}	34.0	47.3	0.71			
Ar^{37}	2.8	3.54	0.79	Fe^{55}	60.8	81.1	0.74			
Ar^{38}	10*	9.1	1.09							

* According to published data (Bibl.32) or E_p = 540 Mev.
** Sum of $\sigma_{Ne}{}^{23}$ (Bibl.32) and $\sigma_{Na}{}^{22}$ (this paper).

The best agreement between calculated and experimental values of σ_{A_1} for an aluminum target is for S = 0.481 and R = 1.65. Since most of the other principal isotopes found in stone meteorites, Mg^{24}, Si^{28}, Ca^{40}, and S^{32}, have atomic numbers and mass numbers close to those of aluminum, the values of the coefficients R and S found by us for Al can also be used for calculating σ_{A_1} for Mg, Si, S, and Ca. The contribution of the nuclear reactions for iron is estimated in the same way as in the interpretation of the effects in iron mete- orites, taking account of the excitation functions of the individual isotopes by applying the appropriate corrections to the iron content of stone mete- /1225 orites. The nuclear reactions for oxygen, which are of fundamental importance for Be^{10}, C^{14}, and H^3, are not considered in the present paper.

The rate of formation of cosmogenic isotopes in chondrites may be estimated by the formula given for iron meteorites (Bibl.11). However, taking account of the chemical composition of the chondrites involves considerable complication of the calculation, and the equation will now be of the following form for the center of a meteorite of radius R:

$$H_{A_i}(R) = \frac{4\pi I_0}{\rho}\left[M_{A_i}\mu_P \cdot e^{-\mu_a R} + \mu_{S_1}\cdot\frac{\mu_{P_1}}{\mu_S - \mu_a} N_{sec.} m_{A_i}\left(e^{-\mu_a R} - e^{-\mu_S R}\right)\right]$$

atoms of A_i for gram per sec .... (6)

where $\mu_P = \frac{N}{\bar{A}_{el}}\rho\bar{\sigma}_P$ is the linear coefficient of absorption of primary cosmic radiation by the elements from which the isotope A_i is formed; N is Avogadro's number (6.02×10^{23}); ρ is the density of matter of the meteorite, equal for chondrites to 3.6 mg/cm^3; $\bar{A}_{el} = \frac{\Sigma A_{el}[M_{el}]}{\Sigma[M_{el}]}$ is the weighted mean of the atomic weight of the elements (A_{el}) from which the isotope A_i is formed; $[M_{el}]$ is the share of an element in the weight of the meteorite; [illegible] $0.75\{\Sigma$ [illegible] $[M_{el}]\}$ [illegible] is the weighted mean cross section of inelastic collision of the primary cosmic rays with the nuclei of the elements from which the isotope A_i is formed; and $(\sigma_0)_{el}$ is the geometrical cross section of the nuclei of the corresponding elements [where $\sigma_0 = \pi R^2$ and $R = 1.37\,(A_{el})^{\frac{3}{4}} \cdot 10^{-13}$ cm].

The cross section of inelastic collision for cosmic radiation of medium energy is 2.76×10^{-25} cm^2 for oxygen; 4.35×10^{-25} cm^2 for silicon; 3.9×10^{-25} cm^2 for magnesium; 4.75×10^{-25} cm^2 for sulfur; 5.8×10^{-25} cm^2 for calcium; 4.2×10^{-25} cm^2 for aluminum, and 7.30×10^{-25} cm^2 for iron. Here,

$\mu_a = \frac{0.835\cdot\rho\cdot N\cdot 0.75\{\Sigma(\sigma_0)_{el}\cdot[M_{el}]\}_M}{\{\Sigma A_{el}[M_{el}]\}_M}$ is the linear coefficient of absorption for primary cosmic radiation by all the elements of the meteorite where the symbol "M" corresponds to the values for the entire meteorite;

[illegible] $\rho\cdot N\cdot 0.$ [illegible] $)_{el}[M_{el}]\}_M$ [illegible] is the linear coefficient of absorption of the

primary cosmic radiation leading to the formation of secondary particles; $\mu_s = \frac{\rho \cdot N \cdot \{\Sigma (\sigma_0)_{el} [M_{el}]\}_m}{\{\Sigma A_{el} [M_{el}]\}_m}$ is the linear coefficient of absorption of secondary particles by the meteoritic matter; $\mu_{s_i} = \frac{\rho N \cdot \Sigma (\sigma_0)_{el} \cdot [M_{el}]}{\Sigma A_{el} [M_{el}]}$ is the linear coefficient of absorption of secondary particles by the elements from which the isotope A_i is formed; $M_{A_i} = \frac{(\bar{\sigma}_{A_i})_{prim}}{\bar{\sigma}_p}$ is the share of the cross section for inelastic collision of the primary cosmic radiation that corresponds to the isotope A_i; $\overline{(\sigma_{A_i})}_{prim} = \frac{\Sigma [illegible] [M_{el}]}{[illegible]}$ is the weighted mean of the formation cross section of the isotope A_i on collision of the primary cosmic radiation with the elements of the meteorite; $m_{A_i} = \frac{(\bar{\sigma} [illegible]}{[illegible]}$ is the contribution /1226
of the isotope A_i to the cross section for inelastic collision of the secondary particles; $\bar{\sigma}_0 = \frac{\Sigma (\bar{\sigma}_0)_{el} [M_{el}]}{\Sigma [M_{el}]}$ is the weighted mean of the geometrical cross section of the nuclei of the elements from which the isotope A_i is formed; $(\bar{\sigma}_{A_i})_{sec}$ is the weighted mean of the cross section for formation of the isotope A_i by secondary praticles; the quantities $(\sigma_{A_i})_{prim}$ and $(\sigma_{A_i})_{sec}$, in the general case, are respective functions of the energy of the primary and secondary cosmic radiation; N_{sec} is the mean number of secondary particles formed by a single nuclear fission. This quantity depends on the energy spectrum of the primary cosmic radiation and on the value of R; I_0 is the intensity of the primary cosmic radiation. In our estimates, we used its maximum value which has been found (Bibl.22) to be 0.65 particle/cm^2-sec-sterad.

In accordance with the above values we next calculated the maximum rate of formation (or rate of disintegration) of cosmogenic radioactive isotopes at the center of a chondrite with a radius of 10 cm, taking account of the chemical composition (Table 4). The resultant values are in satisfactory agreement with the observed rates of disintegration of radioactive isotopes in the Harleton chondrite (Bibl.1). In the Bruderheim chondrite the activity of most of the isotopes was almost double the calculated values. In that meteorite a considerably greater role in the nuclear interactions was apparently played by

TABLE 4

COMPARISON OF CALCULATED AND OBSERVED (BIBL.1) RATE OF FORMATION OF COSMOGENIC RADIOISOTOPES IN CHONDRITES

Isotope	H_S in Atoms/k-min		
	calcul.	Bruderheim chondrite	Harleton Chondrite
Na^{23}	53	90±10	64±7
Al^{26}	39	60±6	45±5
Si^{32}	1.06	—	—
Cl^{36}	5.44	7.5±0.8(5.7[33])	7.0±0.7
Ar^{37}	5.2	13.3÷23*	—
Ar^{39}	5.8	9.4÷11.5*	—
Ti^{44}	0.86	2.0±0.2	1.4±0.2
Sc^{46}	5.2	6.2±0.6	5.4±0.7
V^{48}	14.4	34±7	17±2
V^{49}	29	34±2	20±6
Cr^{51}	36.8	110±27	60±20
Mn^{53}	66.4	85±17	44±8
Mn^{54}	30.3	100±13	38±5
Fe^{55}	54	340±80	⩽80

*Extreme values from the data of many authors [Summary (Bibl.33)].

secondary particles, mainly neutrons, with energies of 100 Mev, which we did not take into account in our calculations. Moreover, the rate of formation of cosmogenic isotopes depends very strongly on the size of the meteorite and on the position occupied in them by the test specimens. These characteristics are unknown for both chondrites examined. To determine these factors, dependable information is required on the spatial distribution of the cosmogenic isotopes in meteorites of various sizes and various chemical compositions, which is a very complicated task, demanding detailed experimental study and complex mathematical work-up.

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